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OIL MINING POSSIBILITIES IN PENNSYLVANIA

By PARKE A. DICKEY

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OIL MINING POSSIBILITIES IN PENNSYLVANIA

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INTRODUCTION

The possibility of recovering oil by underground mining in Pennsylvania became a live subject in 1939. In most of the Pennsylvania fields the gas pressure has been so dissipated that only small quantities of oil are produced per well. Much of the oil still remains in the sands. This oil is of very superior quality and commands a price double that of most western oils. The oil sands are at comparatively shallow depths. It is very logical that any attempts to increase the recovery of oil by underground mining should first be tried in this State.

This paper explains the methods proposed and their difficulties. Optimistic and possibly misleading statements have been made in the press and elsewhere. Although oil mining enterprises are greatly to be desired, no one should invest money in them without a clear idea of the risks and chance of gain. The success of these methods will depend on many complex factors and it is essential that the latest and best theory and practice of petroleum engineering and mining be employed.

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PAST OIL MINING ENTERPRISES

Early attempts at mining oil

Recovery of oil by shafts antedates recovery by wells. Primitive methods of sinking pits or shafts and bailing out the oil that seeped in have been in use for centuries in Europe[1] and Asia.[2] The writer has observed old workings in the province of Boyaca, Colombia, where tar sands were mined by drifts and the asphalt recovered by dumping the sand into hot water.

Apparently the promoters of the Pennsylvania Rock Oil Company, who drilled the first successful oil well in 1859, contemplated the recovery of oil from the Titusville area by trenching and possibly mining. and it was not until 1856 that they decided to drill a well, having noted the oil found in brine wells at Tarentum.[3] Even after production from wells had reached a considerable quantity, mining was attempted. Three shafts were sunk in 1865 about 1 mile north of Greg, Ohio, in an area where shallow wells were very small and short-lived. Only small

[1] Rice, George S., Mining petroleum by underground methods: U. S. Bur. Mines, Bull. 351, 1932.
[2] Day, David T., A handbook of the petroleum industry, 1922, vol. I, p. 140.
[3] Giddens, Paul H., The birth of the oil industry, 1938, p. 47.

quantities of oil were recovered.[4] Another shaft is said to have been sunk near Macksburg, Ohio, in 1865.[5]

In 1864 an 8 by 12-foot shaft was sunk to a depth of 165 feet near Tidioute, Pa., on the site of a well that had produced about 4 barrels of oil a day. The oil sand was encountered at a depth of 152 feet and was 5 feet thick, coarse and pebbly. Several holes 10 to 40 feet deep were drilled down from the base of the shaft, some of which produced water but no oil. Only about 4 barrels of oil per day were recovered from seepage from the walls. The ventilating machinery broke down, an explosion occurred, and the project was abandoned.[6] An attempt was also made to mine First Sand oil near Petroleum Center, Pa.

In 1886, thirty-one oil drainage tunnels were driven into the ' of Sulphur Mountain, Ventura County, California, by th Company of California. Oil seeped from them for many years.[7]

Recent attempts at mining oil in the United States

In 1902 a drift was driven in southwest Colorado a few miles north of Fruita which is said to have been producing 50 barrels per day in 1922, but only 1½ barrels in 1927.[8] In the vicinity of Newport Beach, Orange County, California, an inclined shaft was sunk 505 feet and a tunnel driven 30 feet into the oil sand. A large steam coil was placed in this tunnel to heat the oil, which had gravity of only 5° or 6° API. Within a short time 500 barrels were produced, but the rate of production declined rapidly and the project was abandoned.[9] At Ravenna, Estill County, Kentucky, a shaft sunk 130 feet to an oil-bearing limestone produced 2 or 3 barrels of oil per day.[10] The project was not a commercial success. Near Jacksboro, Texas, where the oil sands are a few inches to 8 feet thick, a 90-foot shaft reached 8 feet below the oil sand. Tunnels were driven in two directions on top of a thin lime cap-rock and small holes were drilled into the sand with 2-inch perforated pipe connected to the sump. The project was apparently not successful.[11] A shaft 99 feet deep in the Electra, Texas, field reputedly yielded 40 barrels per day.[12-13]

Mining oil in the Pechelbronn Field, Alsace, France

A very thorough study of the commercially successful oil mines in France and Germany was made by George S. Rice[1] to which the reader is referred for details. A complete description of the methods used at Pechelbronn, Alsace, France, was written in 1921 by Paul de Chambrier, director general of the enterprise,[14] and a more recent article is by J. Berghaus, formerly chief engineer of the mines.[15]

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[4] Carll, John F., The geology of the oil regions: Pennsylvania 2d Geol. Survey, Rept. III, 1880, p. 430.

[5] Ohio Geological Survey, vol. 6, 1888, p. 451.

[6] Carll, John F., Geological report on Warren County: Pennsylvania 2d Geol. Survey Rept. I 4, 1883, p. 343.

[7] Orcutt, W. W., Early oil development in California: Am. Assoc. Petroleum Geologists Bull. v. 8, p. 64, 1924.

[8] Rice, George S., op. cit. p. 73.

[9] Uren, Lester C., Oil mining a coming practical method for secondary production: Nat. Petroleum News, Oct. 5, 1927, p. 74.

[10] Jillson, W. R., A new method of producing crude oil in Kentucky: Kentucky Geol. Survey, ser. 6, vol. 6, 1921, p. 149.

[11] Smith, L. E., New method of producing oil is given first test in Jacksboro field: Nat. Petroleum News, Nov. 5, 1924, p. 63.

[12] Smith, L. E., Panhandle's oil mine in Electra field is near operating stage. Nat. Petroleum News, Nov. 4, 1925, p. 31.

[13] King, H. H., Electra field has oil mine: Oil Weekly, Sept. 4, 1925, p. 31.

[14] de Chambrier, Paul, Exploitation du petrole par puits et galeries: Dunod, Paris, 1921.

[15] Berghaus, J., Die Oelgewinnung in den Erdölschachtbetrieben von Pechelbronn: Petroleum, vol. 31, no. 35, Sept. 2, 1935.

The Pechelbronn field was known in the Middle Ages, and attempts at mining oil were made as early as 1735. Mining continued in a small way until 1879, when drilling supplanted it. In 1916 mining methods were again attempted.

[illegible] il-b[illegible]ng sands range up to 30 feet thick and lie between beds [illegible] marls. The sands are uncemented but firm. The marls are [illegible] material, though they are more easily picked. They [illegible] under roof pressure, and close timbering is required for t[illegible] aber of vols. has [illegible] The strata dip generally 5° to 6° easterly, but the dips are [illegible] faults are common.

No [illegible] for the porosity, permeability or saturation of the sands are avai[illegible] as these terms are at present understood. De Chambrier estimated in 1921 that a metric ton of undrained sand contained 120 kilograms (equivalent to about 2300 barrels per acre foot) or 12 per cent by weight of oil, of which 16.3 per cent was recoverable by wells and 43.3 per cent by drainage in mine galleries, leaving 40.0 per cent in the sand. These estimates were made before the analysis of oil sands had been standardized and probably are too high.

In 1933 from three shafts, the workings comprised a system of drainage levels and inclined cross-cuts which divide the oil sand layers into rather irregular blocks averaging 300 feet across. Previous to 1922 the tunnels were driven with their floors at the base of the oil sand, and a ditch in the underlying marl carried off the oil. This method proved inconvenient and dangerous owing to the presence of oil on the walls and floor. In 1919 the method was modified so that the base of the tunnel was in the upper, dry part of the sand, and a deeper drainage ditch extended to the base of the oil sand. This ditch was covered. In 1925 the practice was changed again, and the galleries are now driven entirely above the oil sand. (Fig. 1) At intervals of about 10 meters (33 feet) pits are dug through the oil sand. Oil collects in the pits, which are emptied by suction pumps at frequent intervals. In 1934 there were 7000 such pits, each producing an average of 30-40 liters (8-10 U. S. gallons) daily. In 1939 six shafts were in operation and a seventh being sunk.

In order to locate stray sands, holes are drilled vertically up and down at intervals of 10 meters in each gallery. After natural production from these holes has ceased, special pressure holes 35mm. (1.4 inches) in diameter are drilled and ½ to ¾ inch pipe cemented in. Air is injected either continuously or, less often, the producing holes are closed and the pressure allowed to build up, whereupon they are opened.

Other references on Pechelbronn follow:

Forissier, L., Les observations effectuées dans les sondages de Pechelbronn en vue de l'exploitation par galeries: Congrès International de Forage, Paris, Sept 1929.

Forissier and Blocsch, Mining for oil in Pechelbronn: Oil and Gas Journal, vol. 26, no. 12, 1929.

Hoctin, L., Situation de l'exploitation du pétrole à Pechelbronn: Congrès International des mines, Liege, June, 1930.

Uren, L. C., Oil mining at Pechelbronn: Petroleum Engineer, Feb. 5, 1934.

Stein, F., Ueber den Erdoelbergbau in Pechelbronn: Petroleum Zeitschrift, no. 35, 1934.

Loiseau, J., Irruptions de gas, d'huile et de sable dans les mines de Pechelbronn: Comptes Rendus des Géologues Pétroliers de Strasbourg, 1935.

Schnaebele, R., Evaluation des ressources en huile d'un gisement à drainer par galeries dans le champ de Pechelbronn: Congrès International des Mines, Paris, October, 1935.

Forissier, L., Le sécurité dans l'exploitation du pétrole par galeries à Pechelbronn: Congrès International des mines, Paris, October, 1935.

Water drives have been tried, but apparently were not particularly successful, since it is stated that they are used only exceptionally.

Advance holes 4.5 meters (15 feet) deep are drilled from the face of the tunnels as they are lengthened, as a protection against out-rushes of gas, oil, or water.

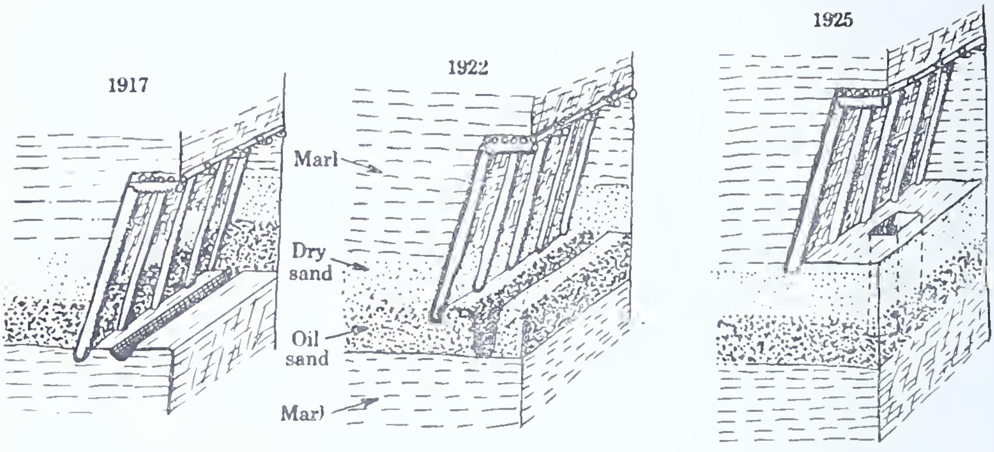


Figure 1. Successive positions of gallery in relation to oil sand at Pechelbronn.

Originally the Pechelbronn mines had only one shaft, but after 1919 the authorities compelled the sinking of a second shaft for escape-way and ventilation at each mine. Gas filters into the mine from the walls, and rarely blows from the face of a heading. An analysis by de Chambrier gives

Methane	80.0
Saturated hydrocarbons	16.0
Olefines	00.5
Carbon dioxide	0.3
Nitrogen	3.0
Oxygen	0.2
	100.0

It is stated that before the gas proportion in the air became dangerous from an ignition point, men began to have headaches and sore throat (Rice, op. cit., p. 27). In 1925 the Clemenceau mine had two fans with a capacity of 105,000 cubic feet per minute, the Le Bel mine one fan with a capacity of 105,000 and another of 70,000 cubic feet, and the Daniel Mieg mine two fans of the same capacity as those of Le Bel. Berghaus states that the ventilation is 3 to 6 cubic meters per man and shift (100 to 200 cubic feet). The mine is rated as gassy, and the men wear storage battery lamps. No explosives are used, and digging is done with pneumatic picks. All power for pumps and other machinery is compressed air, and incandescent bulbs are not used, even in the main haulage ways.

Rice[1] gives complete production data from 1918 to 1929, and Berghaus[15] gives the figures for 1934. In 1934 the total cumulative production of the three mines was 464.200 tons (about 3,250,000 barrels) and there were 180,000 meters of drainage tunnel. No production figures are available for 1939, but it is stated that the total cumulative recovery per hectare of surface drained was 475 tons (about 1350 barrels

per acre). This seems a very poor recovery even if de Chambrier's estimates of the original oil content of the sand are too high.

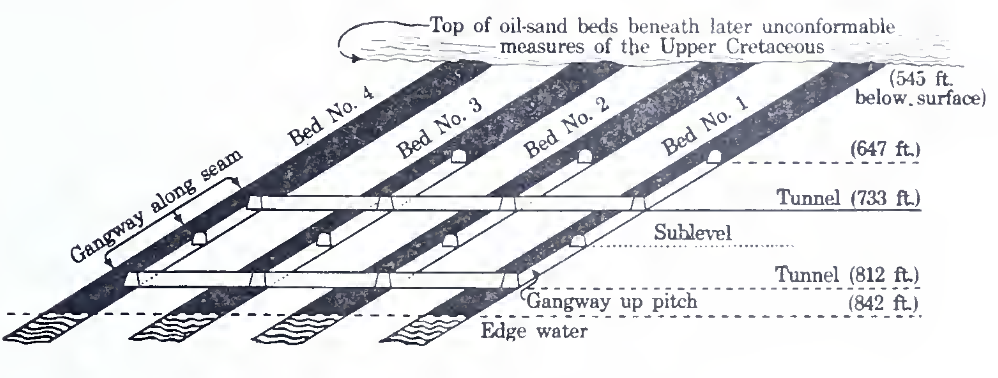
Rice estimates that in 1923 the production was about 1.4 U. S. barrels per shift of 8 hours, and in 1928, 0.98 barrels. He estimated the cost of production in 1923 as $2.06 per barrel and in 1928 as $3.40. Berghaus states that the cost in 1934 was 6.50 to 7.00 RM per 100 kilograms ($3.67 to $3.94 per barrel at 100 kg.=0.7 bbl. and 1 RM=$0.394).

Mining oil in the Province of Hannover, Germany

The Principal oil fields of Germany are in the Province of Hannover. The oil sands are tilted, in places steeply, around the flanks of "salt domes" which have been thrust upward through about 10,000 feet of sedimentary beds. The Wietze field in 1929 had produced about three-fourths of the total production of Germany, at that time 14,000,000 barrels.

Rice[1] gives a complete description of the Wietze field, which he visited in 1923 and 1929. More recent articles by Walter Sack[16-17] have appeared in journals published in the United States.

Mining was undertaken at Wietze in 1919 by the Deutsche Erdoel Aktiengesellschaft, which had developed and operated the Pechelbronn mines until Alsace was ceded to France. Four oil sands dip 6°-8° northerly in the area of the mine, though more steeply elsewhere. The oil is limited down-dip by edge water at a depth of 842 feet, and up-dip by an unconformity where the edges of the oil sands are truncated and overlain by Upper Cretaceous beds. The sands are uncemented, are thicker and softer than at Pechelbronn, and range from 12 to 50 feet thick. The oil is heavy (0.94), and gas is practically absent.



(Not to scale and not showing true dip of beds)

U. S. Bureau of Mines Bull. 351

Figure 2. Diagrammatic vertical section of oil sand beds at Wietze.

In 1929 there were two shafts, 842 feet deep, with main landings at 733 and 812 feet from which main crosscut levels were driven to cross the four sand beds. At the intersection of each oil-sand bed, branch tunnels turn into it, and from these, inclined passageways for rope haulage run up and down the dip. (Fig. 2.) From the inclines sublevels turn off so that the mine is developed into somewhat irregular blocks

[16] Sack, Walter, Reviving production of a nearly exhausted German field by penetrating sands from below: Oil Weekly, July 6, 1936.

[17] Sack, Walter, Method for economically sinking oil shaft at Haenigsen-Nienhagen: Oil Weekly, March 15, 1937.

about 100 to 200 feet square. The air is coursed as in coal mining. The tunnels were driven in the sand and had to be heavily timbered and lagged. In particularly soft material forepoling was sometimes required. The pressure of the strata is great and difficulty is experienced in keeping the permanent entries open. The oil drains into troughs and ditches, and is bailed from sumps in the headings. Pipe lines transport it through the main entries and it is pumped to the surface through special bore holes.

The fourth or uppermost sand bed is much finer than the others, and the oil does not drain freely from it. In 1929 it was being mined by the longwall method and hoisted to the surface. The oil was extracted by hot water and soda salts, the sand allowed to drain for a period and returned to the mine by belt conveyors for packing. This process was admittedly experimental and expensive, but recovered all but about 10 per cent of the oil originally in the sand.

Although less gas occurs in the sand than at Pechelbronn, storage battery lamps of permitted type are used. Explosives are not necessary. Electricity is used, but there have been no serious fires or explosions. The accident rate compares favorably with other German mines.

The production per month in 1929 was about 600 tons (4200 bbl.) of "mined" oil (from the extraction at the surface of sand from No. 4 bed and the galleries in the other beds) and 1900 tons (13,300 bbl.) of "drainage" oil. This was equivalent to .0267 tons (1.87 bbl.) per man-shift from the mine. Rice estimated the cost as $3.45 per barrel.

More recently, according to Walter Sack,[16] another shaft was sunk with crosscuts running southeast at the 350-foot level and northeast from the 700-foot level, below the oil sands. At 600-foot intervals drifts were driven at right angles to the crosscuts and parallel to the strike of oil sands but beneath them. Every 50 feet along these tunnels 7 holes were drilled fanwise upward into the sand. It is reported that the holes yield 2 barrels per hour, or 250 barrels per hour per 500 feet of tunnel.

Conclusions regarding previous attempts at oil mining

The attempts at oil mining in the United States are almost all on a small scale and were not carried far enough to work out a technique or to determine their practicality. There has been an abundance of oil from wells, and the low price of oil has never made mining seem attractive.

Rice (1, p. 71) says with regard to the European oil mines:

> "From a purely technical standpoint the results so far obtained have been successful and are being improved as experience is gained. Commercially, also, the results appear to have been successful under the conditions of limited natural oil resources and as a necessary consequence of the great need for petroleum products in the respective countries and of relatively high prices in their markets. Petroleum that has remained in the ground after a number of years of oil-well development and pumping, until the project no longer is remunerative, has been recovered by underground mining and drainage methods, to the extent, it is claimed, that an additional 40 per cent of the original content of the sand has been obtained from areas from which 20 per cent had previously been obtained by wells from the surface.
>
> "Whether or not the specific methods used at Pechelbronn and Wietze are applicable in certain fields of the United States with favoring conditions is a question, but the study of those methods is instructive and suggestive of modified methods which the writer

believes may be applicable in at least some of the oil fields in America in which oil permeability of the sands is poor, where mining conditions are favorable and the petroleum is of such special quality that a relatively high price is obtainable."

Conditions favorable to oil mining

Certain definite conditions must be present before mining can be contemplated in 1939, and other conditions, though less essential, may determine whether the enterprise is a success or failure. Some of these are listed by Rice (op. cit. p. 100) and are given here, somewhat modified by the author.

1. The character of the crude oil in the field should be such that it brings a relatively high price. Rice concluded in 1922 that "it would not be wise to assume that the cost of production by mining including all operating costs and capital charges can be done with present labor and supply costs in the United States at less than $2.00 per barrel and then only under favorable conditions." Although shaft sinking by large diameter drills and horizontal drilling (to be described) may be applicable to oil mining and may reduce costs somewhat, this conclusion still seems valid, at least until the method has passed the experimental stage.
2. The district should not contain large quantities of gas under pressure. This means of course that it must be in a drilled field and thus less oil is present in the sand. However, in fields that contain much gas the oil can be produced economically by wells, and mining would not be contemplated.
3. The sand should contain a minimum amount of water, preferably under low hydrostatic head.
4. The sand should contain a sufficient quantity of oil. It is naturally quite impossible, with no experience, to define the limit of leanness of a sand that would be profitable to mine. In the following discussion it will be assumed that mining should not be attempted unless the sand contains 8000 barrels per acre of which 3000 barrels are recoverable. An obvious corollary of 2 and 4 is that mining should not be undertaken until enough core holes are drilled to determine accurately the thickness and fluid content of the sand. Experimental attempts involving small investment, such as drilling horizontal wells into an outcrop, might be advisable in a sand containing less than 8000 barrels per acre, but a shaft should be sunk only in an area known to be rich.
5. The sand should be thick, continuous, and not markedly lenticular.
6. The sand should be of sufficient permeability to allow the oil to move by free gravity drainage or light pressure of air or water. Heavy pressure would make mining operations more complicated and dangerous.
7. There should be a good, firm shale, at least 15 feet thick, above or below the oil sand, through which tunnels can be driven by machinery, preferably without blasting. (Items 6 and 7 are not important if the horizontal well method is to be used.)
8. The strata should dip gently.
9. For initial attempts, depths greater than 1200 feet should not be considered.
10. Adequate acreage should be available. Rice specifies 2560 acres, which is perhaps more than necessary.

It will not be difficult to find a place in Pennsylvania that meets these requirements.

PROPOSED METHODS OF MINING OIL

Rice [1] gives a good summary of the methods that had been proposed up to 1932, and a practical mine layout and plan of operations. Since his paper, however, methods of sinking shafts by large-diameter drills have been developed. Horizontal bore holes may replace tunnels. The various methods will be described briefly.

Shaft sinking

Conventional methods

Methods of sinking shafts are too well known to need description here. An excellent discussion of American methods, with cost data, is to be found in Bulletin 357 of the U. S. Bureau of Mines.[18] A good recent discussion of the European and South African methods is by Bernard Beringer.[19]

Square or rectangular timbered shafts are most commonly used in the Pennsylvania coal regions. A shaft 14 feet square can be sunk for $100 to $250 per foot, including timbering or concreting, barring excessive gas or water. For depths less than 500 feet the cost is less, ranging probably from $60 to $100 per foot.

For oil mining Rice recommends a circular shaft lined with concrete. Circular shafts are used more in Europe than in the United States, and have much to recommend them. Beringer [19] also points out their numerous advantages; they are cheaper to sink and equip, are much stronger in heavy ground, and are much more efficient for ventilation. If it is desired to penetrate the oil sand, the shaft or chamber should undoubtedly be lined with concrete, and it should be circular if there will be high pressures in the sand. Rice (1, p. 146) estimates the cost of a circular shaft 18 feet in diameter, lined with concrete, as $150 per foot.

Drilling

In recent years a method has been developed for drilling large (30-inch) diameter holes by rotating a hollow steel cylinder with chilled steel shot for abrasive. A soft steel band riveted to the cylinder provides a cutting shoe, and notches are cut in it so that the shot can settle to the bottom of the kerf and be ground against the rock by the drill above. After a few feet have been drilled the cylinder is removed. The core is broken loose by wedges and if possible lifted out whole by a puller provided with dogs on a contracting ring which slips over the core. The time required to remove the drill and break down the rods, and the whip of the rods make it impossible to drill a very large or deep hole. Such holes are principally for the inspection of bedrock at dam sites.

More recently, the Idaho-Maryland Mines Corporation has succeeded in drilling holes of larger diameter to depths greater than 1000 feet.[20-26]

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[18] Gardner, E. D., and Johnson, J. Fred. Shaft sinking practices and costs: U. S. Bur. Mines Bull. 357, 1932.

[19] Beringer, Bernard, Underground practice in mining. 2d edition: Mining Publications, Ltd., Salisbury House, London, 1938.

[20] Newsom, J B., Boring a 5-foot shaft 1125 feet deep at the Idaho Maryland Mine: Min. and Met., Sept., 1936.

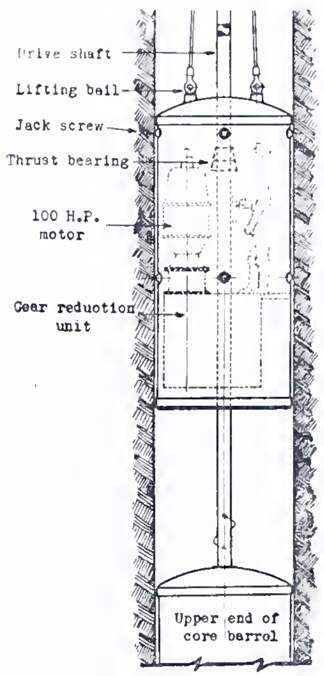
[21] Newsom, J. B., New advance scored in boring holes of large diameter: Eng. Min. Jour., Oct., 1938.

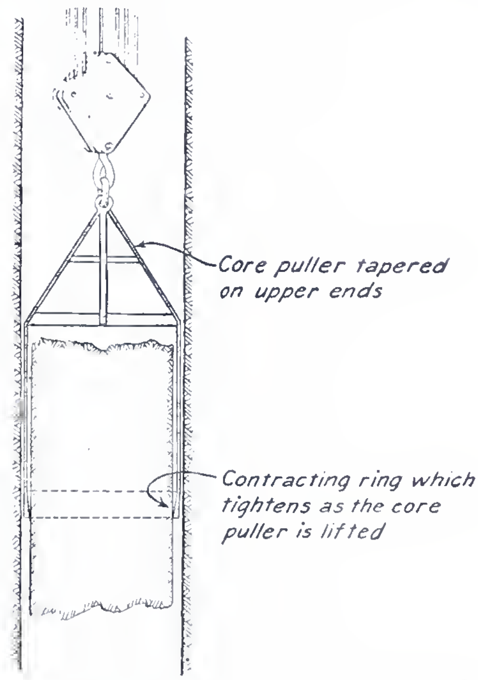
[22] Richards, B. S., Sinking a ventilation bore hole in Minnesota: Min. Congress Jour., Oct., 1938.

[23] Moneymaker, B. C., and Fox, P. P., Large-diameter core drill for geologic exploration: Am. Inst. Min. Met. Eng., Tech. Pub. 1000 (Mining Technology, Nov. 1938).

[24] Tierney, The calyx core drill: Min. Congress Jour., Nov., 1938.

The power plant, consisting of a cage in which is an electrically operated motor and a place for the operator, is lowered down the hole immediately above the drilling cylinder. It is held steady against motor torque by eight screw jacks which clamp against the wall of the hole. (Fig. 3). After sinking 8 or 10 feet the drill is lifted out and the hole bailed of accumulated seepage water. The core is then broken with hand-operated wedges, and the core puller sent down. (Figs. 4 and 5). After the core has been removed, any broken rock is mucked out by hand. When many minor operating difficulties had been worked out,





Cuts from A. I. M. E. Technical paper 1068

Shaft sinking with large diameter shot drill at Ely, Minnesota.

Figure 3. Generalized section of core drill.

Figure 4. Method of lifting cores.

the method proved to be safe and fast. The drilling of the Ely, Minnesota, hole is summarized by Newsom and Haselton (26, p. 9) as follows:

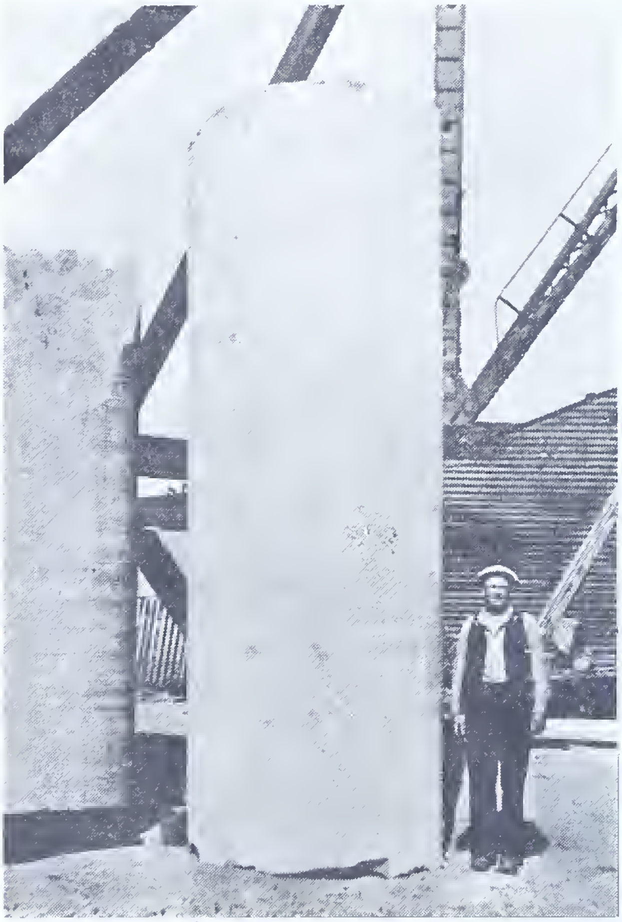
> Hole size, 5½′ diameter, depth 1208′ (1193′ bored plus 15′ alluvium). Started April 1, 1938; finished Oct. 30, 1938. Man hours, 11,044; crew hours, 4933; crew days, 205.5. Average advance per day, 5.8 feet (177 feet per month); best week, 77 feet. Drilling speed, 2.05 feet per hour during best week; number of drill cycles, 141; length of average cycle, 8.46 feet; time consumed by average cycle, 35 hours. Direct final cost sheet, covering power, direct labor (drillers and hoist men), surface men, shop labor, supervision, shot, oil and grease, and all other direct charges incurred during boring, shows the following cost per foot: labor and supervision, $12.16; power, material, $7.34; total, $19.50.

Probably such holes could be sunk successfully in Pennsylvania. Loose or heavy ground requiring much hand mucking would increase the cost considerably, but holes 30 inches in diameter have been drilled in rocks like those of the oil regions without difficulty. Drilling an initial

[25] Newsom, J. B., and Jackson, C. F., Shaft sinking with a shot drill: U. S. Bur. Mines, Inf. Circ. 6923 (1936).

[26] Newsom, J. B., and Haselton, W. D., Borehole at Zenith Mine, Ely, Minnesota; Am. Inst. Min. Met. Eng., Tech. Pub. 1068 (Mining Technology, May, 1939).

5½-foot hole with rented equipment or by contract probably would cost $50 per foot, not counting the concrete lining, which probably would add $25 per foot. Considering the diameter, which would be too small for any extensive operations, the cost is not remarkably cheaper than sinking by conventional methods. The greatest advantage of drilling is that blasting is not necessary and the walls are left in much better



Cut from A. I. M. E. Technical paper 1068

Figure 5. A 14-foot core at Ely, Minnesota.

condition. Sealing off water-bearing sandstones during the drilling would be possible, probably by enlarging the hole slightly by hand and cementing casing opposite the sand. Apparently the greatest flow of water at Ely, Minnesota, was 10 gallons per minute. Flows up to 100 gallons or more per minute may be anticipated from the "Mountain" sands in the oil regions.

Underground workings

Mining the sand

Unquestionably the oil in the sand can be recovered most completely by mining it like coal or ore and extracting the oil with solvents or alkali solutions. Even at Wietze, however, this method was not considered to be a commercial success, and Rice estimated that it cost $4.50 per barrel without "general expense" and "capital charges." An oil sand with 800 barrels per acre-foot would contain only one-half barrel per

cubic yard or one-third barrel per long ton. The Pennsylvania oil sands are all consolidated, and some are very hard and would require explosives in mining. If the sand could be mined and hoisted for $1.50 per ton, and treated for $0.50 per ton, oil would have to be worth more than $6 per barrel to pay.

Drainage tunnels in the sand

This method was used originally at Pechelbronn and Wietze, and apparently has been abandoned at both places. Oil and gas seeping from the walls made great fire hazard and bad working conditions. Driving tunnels in the hard sandstones of the Pennsylvania fields would require explosives and would be expensive and dangerous. Stimulative methods, such as water flooding and air repressuring, would be difficult or impossible to apply. The advantage is the large surface exposed to seepage.

Tunnels immediately above sand, with pits to base of sand

The method used at Pechelbronn of driving tunnels above the sand and sinking pits to the base of the sand is not adaptable to Pennsylvania, because of the hardness of the oil sands and the presence of more gas. Figures 6 and 7 are plans for mining oil by means of tunnels under sand and diagonal boreholes upwards to the sand, suggested by George S. Rice.

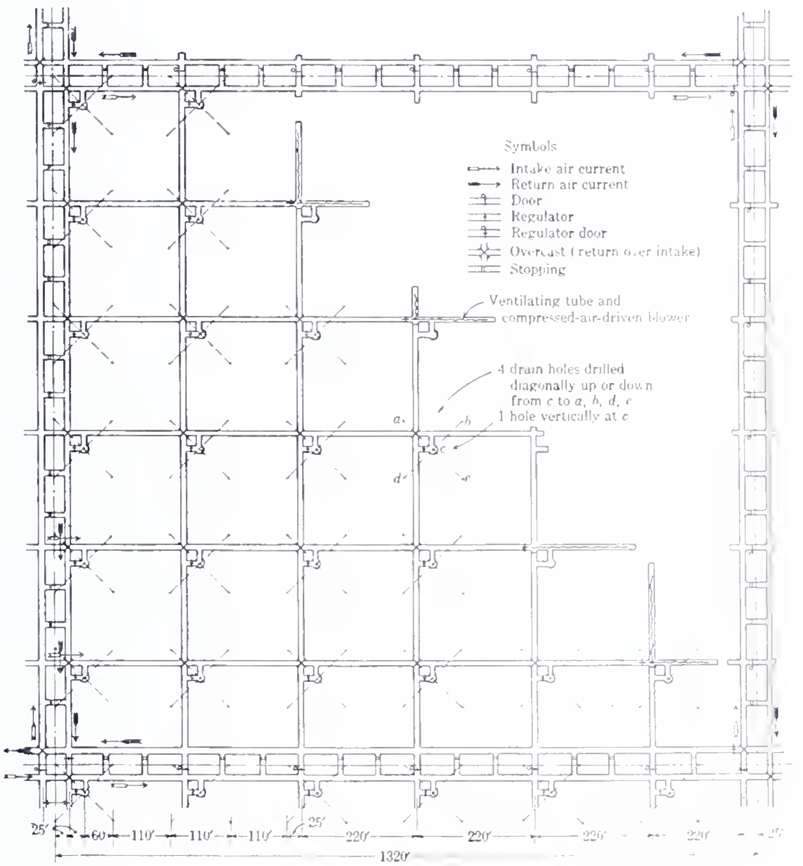


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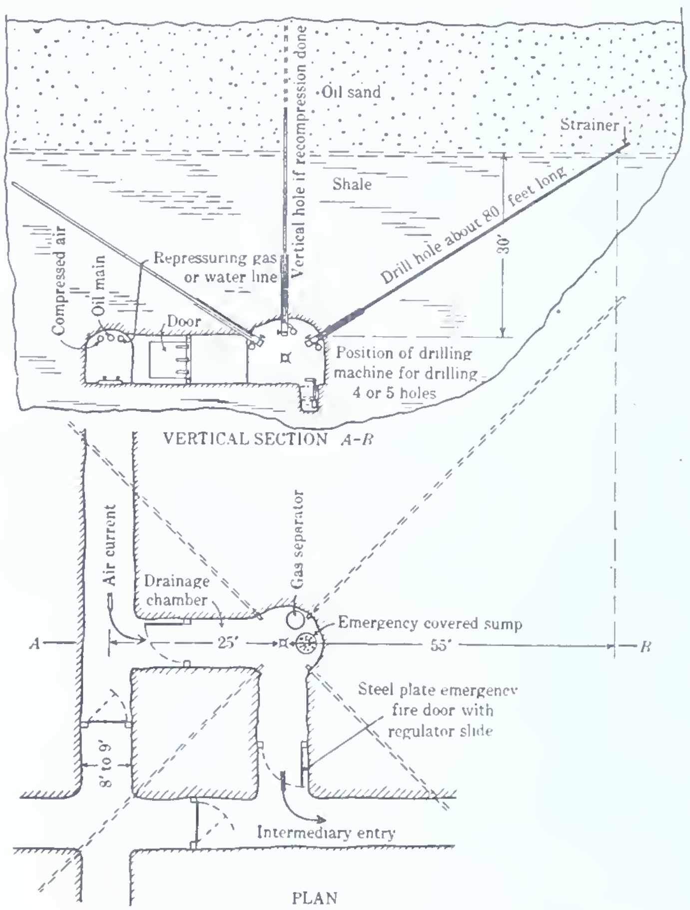
Figure 6. Layout of entries in block form and diagonal drainage holes.

Tunnels above or below sands and boreholes up or down into sands

The method of driving tunnels above or below the sands and raising or sinking boreholes into the sands apparently is successful at Wietze

and Pechelbronn. It was advocated by Rice,[1] who suggested double main entries around 40-acre blocks, and single entries dividing each block into 36 squares, 220 by 220 feet. (Fig. 6). At the intersection of the single entries a special chamber is suggested, from which 4 or 5 holes are drilled, one vertically upward and the others at an angle so as to intersect the oil sands. (Fig. 7). An alternative plan proposes driving a series of long, parallel double entries, 330 feet apart. Holes are drilled up or down at 100-foot intervals in crosscuts. Water is injected into alternate series of holes to provide a line drive.



U. S. Bureau of Mines Bull. 351

Figure 7. Vertical section and plan showing drainage points by drill holes from spaced chambers in Figure 6.

Apparently this method was originally proposed by Paul Casamajor (U. S. Patent 50,902) in 1865.[27] The details of this method have been elaborated by Leo Ranney,[28] who has patented numerous devices and methods for the bore holes, which he calls "mine wells," and devices for testing the sand, application of heat, gas, oil, and water separators, etc.

The advantage of this method lies principally in its adaptability to

[27] Bignell, L. G. E., Oil mining patents date back to 1865: Oil and Gas Journal, June 21, 1928.
[28] Ranney, Leo., U. S. Pat. 1,634,235, June 28, 1927.
U. S. Pat. 1.634.236, June 28, 1927.
Other patents by Ranney are:

1,660,818	1,812,305	1,884,858	2,048,710
1,667,269	1,811,506	1,884,859	2,057,691
1,700,952	1,811,561	1,851,446	2,126,575
1,806,499	1,870,869	1,867,758	2,126,576

water flooding and repressuring. For water flooding Ranney[29] recommends tunnels 300 to 600 feet apart, with vertical bore holes to the sand 20 to 30 feet apart, alternate tunnels being water-injection and oil-producing series. Close watch is kept on the pressures of the injection holes and the production of the oil holes. He claims that close control of the wells makes it possible to control the advancing front in the various sand beds and to keep the water from bypassing through the more permeable beds.

For tunnels 300 to 600 feet apart, pressures of air or water comparable to those now in use would be necessary. For water flooding these are often over 1000 pounds per square inch. It might be difficult to seal off the relatively short holes in such a manner as to withstand these pressures.

L. C. Uren[30] suggests that lines of test borings be drilled perpendicular to the advancing bank of water in a line drive. Reagents (such as soda or one of the newly discovered organic detergents) are dissolved in the water. As the front advances, samples of the water are taken near the water-oil contact, and when the reagent shows signs of becoming exhausted a cross current of fresh solution is set up parallel to the advancing front.

Ranney states that tunnels above or below the oil sand can be kept free of oil or gas. All drilling is to be done through stuffing boxes.

The principal purpose of this method of mining is to increase enormously the number of holes that can be economically drilled into the sand, i. e. decrease the spacing. While decreasing the spacing undoubtedly decreases the time necessary for the extraction of oil, it is doubtful if it increases materially the ultimate recovery. This is true both for original drilling[31, 32] and for secondary methods such as water flooding.

Muskat has shown that although the conductivity of a water-flood pattern increases rapidly with closer spacing, the efficiency, within limits, is quite independent of it.

Tunnels above or below the sand, with channels cut through it

J. L. Rich[33-35] has suggested driving the tunnels above or below the oil sand and cutting channels through the sand. This would expose vastly greater surface of sand than the previous method and would provide more rapid if not more complete recovery. Rich suggests cutting the channels with endless travelling wire as is done extensively in quarrying. It should be entirely possible to cut a slot by drilling two holes in the floor of a tunnel, 50 to 100 feet apart. An endless wire actuated by a drum would pass down one hole, around a pulley, back to the floor of the tunnel and along the floor to the next hole, down around a pulley and back to the drum. As the wire travels, water and abrasive (shot or sand) is fed into the slot formed by the wire, which gradually cuts into the rock below it until it is at the

[29] Ranney, Leo., Oil mining for the Pennsylvania fields: Engineers' Soc. of Western Pennsylvania, Proc.. vol. 47, no. 6, June 1931, pp. 315-348.
[30] Uren, L. C., U. S. Pat. 1,735,481, Nov., 12, 1929.
[31] Kraus, Edgar, The geologist and the well-spacing problems: Bull. Am. Assn. Petroleum Geologists. vol. 22, no. 10, October 1938, pp. 1440-1446.
[32] Muskat, M., Flow of homogeneous fluids in porous media: McGraw-Hill, 1938. p. 519.
[33] Rich. J. L., U. S. Patents 1,507,717; 1,679,683; 1,735,012; 1,773,407.
[34] Rich, J. L.. Possibilities of petroleum recovery by mining: Eng. Min. Jour.-Press, June 6, 1925, pp. 919-924.
[35] Rich, J. L., Proposed method of oil recovery by combined mining and flooding: Petrol. Development and Technology in 1926. A.I.M.E., 1927.

level of the pulleys. This method might be cheaper than drilling closely spaced holes, but would probably involve greater fire hazard.

A somewhat similar idea was had by C. F. Jackson,[36] who proposed breaking the oil sand by "artificial faults." Parallel entries were to be driven beneath the sand, and then the pillar between was to be crushed by firing simultaneous charges of explosives in the pillar and the overlying oil sand. A section of the sand over the pillar would then settle, or at least would be thoroughly cracked.

Horizontal holes drilled radially from the foot of a shaft

A method apparently envisioned by Casamajor[28] and Wright[37] and also suggested by Ranney[38, 39] is that of drilling horizontal holes radially

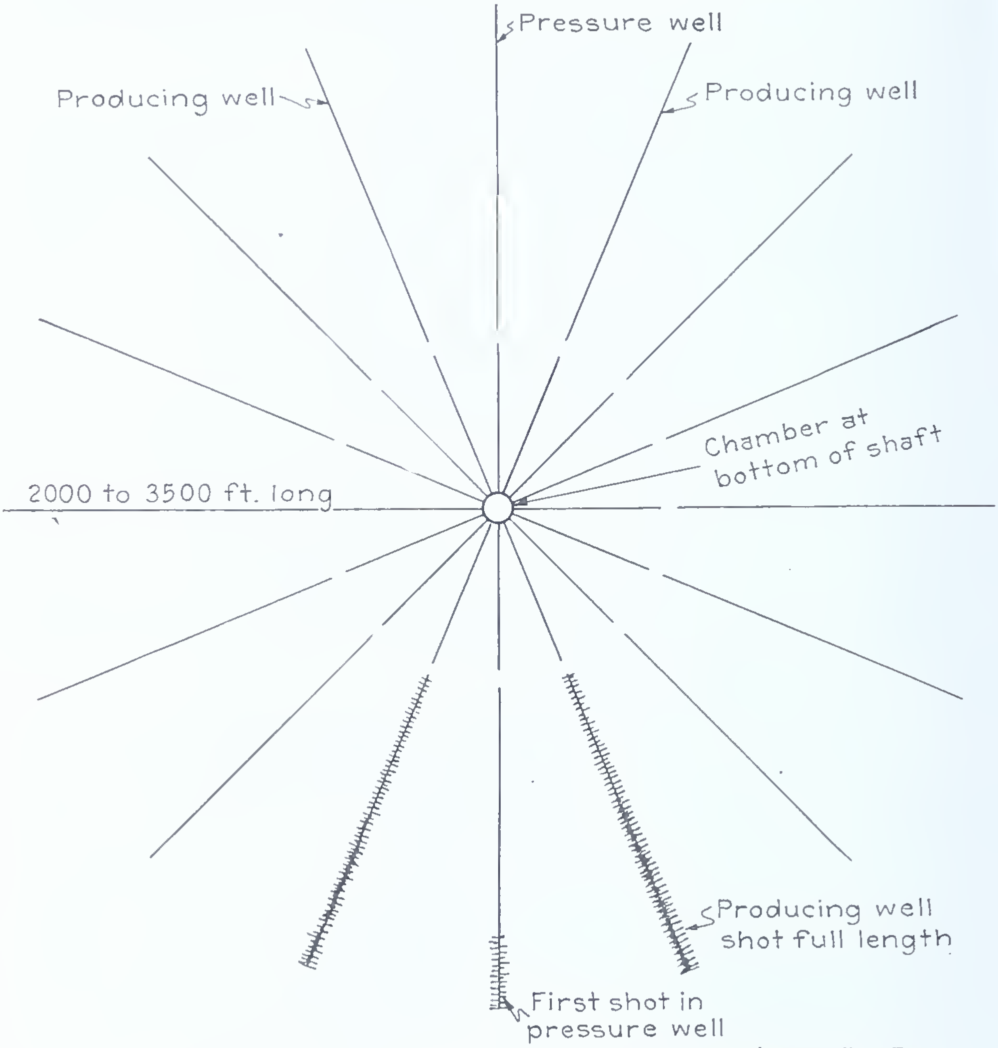


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Figure 8. Plan of proposed method of drilling horizontal wells from the foot of a shaft.

from the foot of a shaft. (Figs. 8 and 9). Drilling long holes in a horizontal direction with a diamond drill to get advance information on tunnels and mine galleries has been common practice for more than

[36] Jackson, C. F., U. S. Patent 1,804,692, May 12, 1931.
[37] Wright, Robert L., U. S. Patent 1,520,737, Dec. 1924.
[38] Ranney, Leo, U. S. Patent 1,811,560, June 23, 1931.
[39] Ranney, Leo, Horizontal drilling through outcrop brings results. Oil and Gas Journal. April 20, 1939.
[39a] Ranney, Leo, The first horizontal oil well, Petroleum Engineer, June, 1939.

50 years. As an experiment in oil mining, Mr. Ranney drilled a hole in from an outcrop of the First Cow Run sand near McConnelsville, Ohio. (Fig. 10). The sand here is about 28 feet thick. The upper three feet are fine, hard and impermeable, below which are four feet of good pay sand. There follow 7 feet of fine, hard, impermeable sandstone, and the lower 14 feet are pay sand. The field was discovered in the 1860s, and in recent years had been subjected to both vacuum and pressure. It had not been operated since 1930. A cable tool well

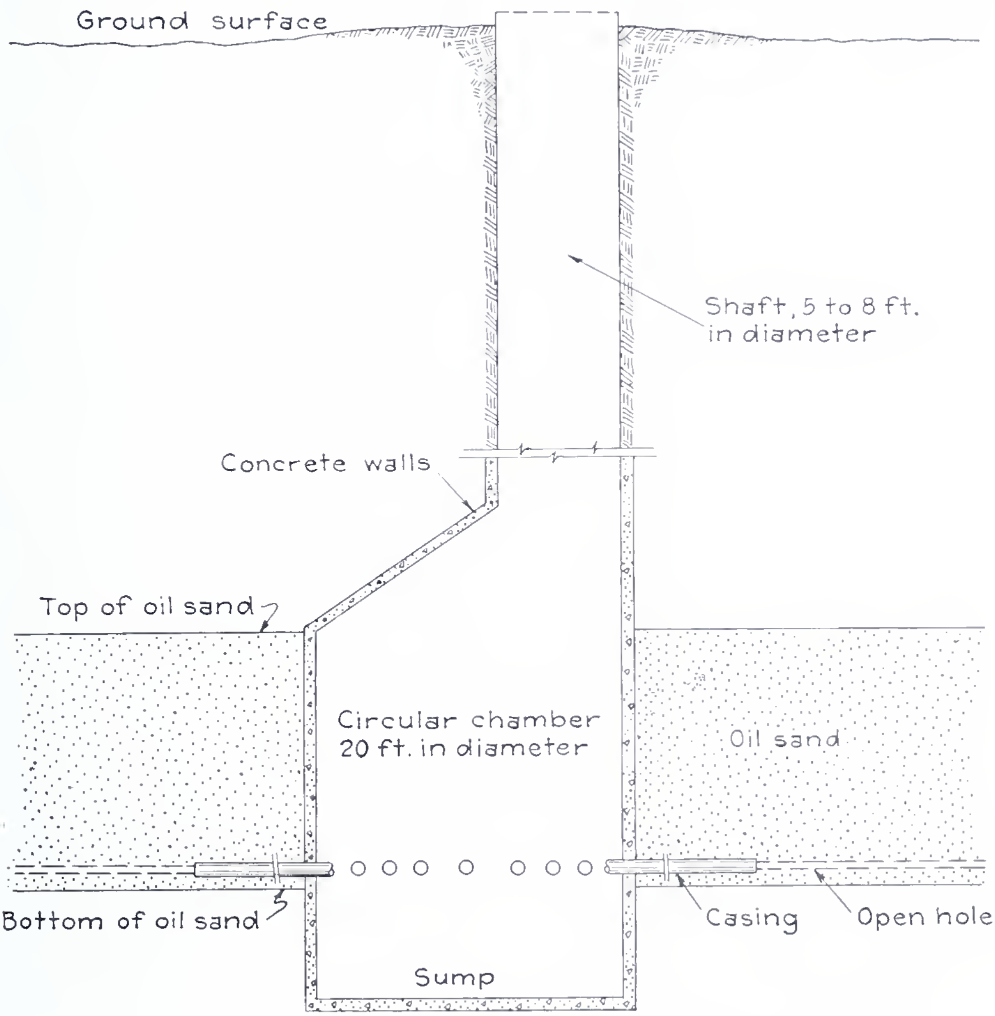

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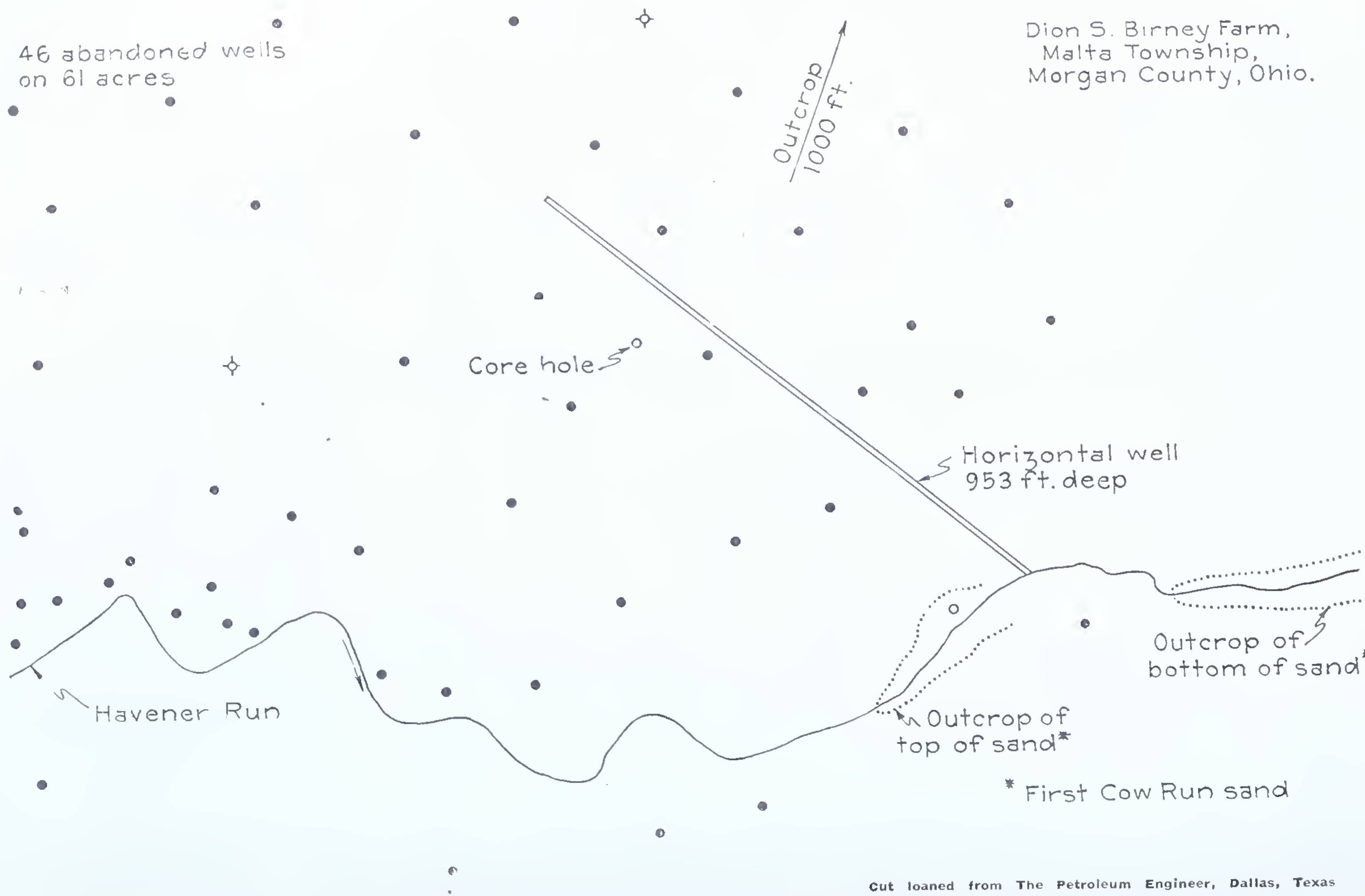
Figure 9. Vertical section of proposed method of drilling horizontal wells from the foot of a shaft.

which was cored, located 700 feet in from the outcrop and about 40 feet from the horizontal well, showed a porosity for the upper pay of about 16 per cent and an oil saturation of 16 per cent. The lower pay showed a porosity up to 20 per cent and oil saturation of 17.5 per cent. The permeability of both pays was high and quite uniform, ranging from 150 to 750 millidarcys. The oil content was quite low, and was estimated as 4200 barrels per acre for the 18¼ feet of pay sand.[40]

The horizontal well was started in the upper pay and drilled almost level for 802 feet. Later a branch hole was drilled from 630 to 953

[40] Ranney, Leo, Personal communication.



Cut loaned from The Petroleum Engineer, Dallas, Texas

Figure 10. Sketch of tract near McConnelsville, Ohio, showing horizontal well drilled from outcrop by Leo Ranney.

feet. The branch was believed to have descended 8 or 9 feet, and to have finished in the lower pay.

The well was drilled with a conventional diamond drilling machine with a rotatable hydraulic having a 2-foot feed, powered by a 25 hp. gasoline engine. The hole was 2⅝ inches in diameter. At times the drill advanced at the rate of one foot per minute, and in one 7-hour shift 106 feet of hole was made. The average rate of drilling on the first hole was 40 feet per shift.

Three times during the drilling, gas and oil spouted from the hole, which doubtless penetrated pockets in the sand that had formerly been sealed off so that escape of their contents to the outcrop or to the old wells had been prevented.

The hole was shot with 1150 pounds of 80 per cent high velocity gelatine in sticks 2 inches in diameter. Great lengths of dynamite cannot be fired from a single point, since the compression wave travels faster than the ignition wave and the compressed explosive will not fire. Accordingly a fuse of TNT (Cordeau-Bickford) was laid alongside the dynamite, with blasting caps attached at short intervals.

After shooting, the well blew for about 20 minutes and then flowed by heads for about an hour. It is estimated that several hundred barrels flowed out, but this oil, which was confined behind a dam, was lost during a washout of the creek. The hole was found to be open clear back, and was cleaned out by washing. Large quantities of sand were removed.

The well has 3 feet of casing cemented to the rock, and is tubed to 940 feet, the last 10 feet of pipe being perforated. When producing, vacuum applied to this pipe removes the oil collected in the far end of the hole, and is then applied to the casing which removes the oil from the first branch of the hole. The well is said to have produced 9½ barrels in 7 hours after standing two weeks before shooting. As it has never been under steady production it is impossible to estimate its potential. However, if the analysis of the cored vertical well is representative of the sand, it is surprising that any oil at all is produced. Quite probably the horizontal well or the shot cracks penetrated richer areas than the vertical cored well.

The method of drilling horizontal diamond drill holes from the foot of a shaft is perhaps the cheapest, and, therefore, most promising of the methods that have been suggested. Mr. Ranney's successful experiment in recovering oil from a sand that contained a very low saturation of oil is encouraging. The method, however, has many disadvantages and technical difficulties which will be discussed in some detail.

SHAFT SINKING

The shaft may be sunk either by conventional methods or by shot drills. Its diameter may be small since there will be little material to be hoisted, and will be limited only by the requirements of ventilation and the size of the drilling machinery. For shaft sinking by hand to a depth of 500 feet, 8 by 12 feet or 10 by 10 feet is probably the smallest possible dimension. For greater depths 10 by 14 feet probably is necessary. An 8 by 12 foot shaft would cost between $60 and $100 per foot, including timbering or lining with concrete. Shot drilling a shaft 8 feet in diameter and 500 feet deep probably would cost between $30 and $60 per foot. Contingencies such as large flows

of water or heavy ground would increase the cost considerably. Drilling several holes in the same district would decrease the cost because the machinery would have to be moved less and the operators would become familiar with local conditions. For purposes of estimation, it will be assumed that sinking the shaft will cost $75 per foot including lining and allowing something for contingencies.

Because large quantities of water should be anticipated in sinking a shaft for an oil mine, holes for grout should be drilled down the center and around the periphery of the proposed shaft. In any case it will be necessary to core completely a well on the site of the proposed shaft in order to know the geological conditions, and the gas, water, and oil that may be expected.

ENLARGING WORKING CHAMBER

The dimensions of the working chamber at the foot of the shaft will depend on the kind of machinery and drill rods used, but 20 or 30 feet laterally and 8 or 10 feet high are probably the smallest possible. The Pennsylvania oil sands are so hard that the rock will have to be blasted. Gas, oil, and water will enter freely while the chamber is being opened, and will present numerous difficulties and hazards. The water will be very salty and highly corrosive to the machinery.

The greatest source of danger will be the methane gas and the heavier hydrocarbon vapors. Although methane is only slightly toxic, the heavier hydrocarbons, which are abundant in Pennsylvania oil, are extremely so, causing headaches, sickness, and sometimes death to those breathing them.

Methane-air mixtures have an upper explosive limit of about 15 per cent, and a lower explosive limit of about 5 per cent methane. The heavier hydrocarbons are explosive at considerably lower percentages.[41] The prevention of explosions will therefore be the greatest problem in sinking the shaft and enlarging the working chamber.

Three methods may be considered. (a) A powerful ventilating air current to sweep away the vapors as they issue from the sand or rise from the oil. Coal-mining experience indicates that an exhaust fan is better than a blower. In view of the considerable flows of gas that may be expected and the large quantities of gasoline vapor in the crude oil, it is believed by some engineers that this method will not entirely eliminate the danger of explosions or toxic effect of the gases on the men. (b) The men to work under a pressure sufficient to hold back any flows of gas. An air lock would be provided near the surface and men and material would be passed through it as they went up and down the shaft. It is hard to predict the pressure necessary to hold back any gas flows. It is doubtful whether pressure would prevent the evaporation of considerable quantities of the heavier hydrocarbon vapors, and the danger of asphyxiation and explosions would still be present. It has been suggested that a pressure of about 20 pounds above atmospheric be supplemented by a pressure less than atmospheric in the surrounding sand, caused by strong suction applied to wells near the shaft. (c) The men to work in helmets in an atmosphere saturated with hydrocarbons above the explosive limit. Methane and gasoline vapor in air in quantities greater than 20 per cent are not explosive. Helmets with oxygen tanks or air hoses such as are used in mine

[41] Coward, H. F. and Jones, G. W., Limits of inflammability of gases and vapors: U. S. Bureau of Mines Bull. 279, p. 29.

rescue work would be required. They cut down the efficiency of the workmen very considerably. However it would probably be advisable to use these helmets even under the ventilation and pressure methods of working, especially during initial attempts. An explosion or a fatal accident at the beginning might seriously interfere with the successful continuation of a project.

Beryllium-copper tools probably should be used to avoid the danger of sparks. They cost much more than ordinary steel tools and wear out faster.

The working chamber would be lined with concrete so that the gas, oil, and water would be completely excluded. It would be possible, as Ranney suggests, to drill through stuffing boxes. Until the technique has been thoroughly worked out, however. there is always danger that the highly explosive gases might enter the chamber.

Owing to the above-mentioned dangers it is very difficult to estimate the cost of the excavation of the working chamber. $5000 will be allowed for the excavation and lining with concrete. This sum may be much too low.

DRILLING HORIZONTAL HOLES

Many thousands of feet of horizontal diamond drill hole have been drilled in mine galleries and tunnels, but hitherto it has not been possible to control their direction with sufficient accuracy to follow a thin oil sand for long distances. In this connection the experience in drilling advance horizontal diamond core holes in the tunnels of the South Penn Turnpike during 1938 is of interest.

It was found that the drill could be operated in a space 8 to 9 feet high, 12 to 15 feet wide, and 30 to 40 feet long. The drill rods and barrel were 10 feet long.

Holes were surveyed with a hydrofluoric acid bottle for deviation in a vertical plane, with an accuracy of one or two degrees. Measuring horizontal deviation with a compass in gelatine was unsatisfactory. The holes tended to descend, especially in passing from soft to hard strata. Controlling them with wedges was unsuccessful. "In Tuscarora tunnel a horizontal bore hole 1450 feet long was drilled between the east and west headings of the tunnel. In order to insure complete penetration to the west heading, after one failure, the new hole was inclined upward approximately 5 degrees. At one place the hole reached a point 18 feet above the proposed tunnel roof line. It ended approximately 4 feet below the proposed tunnel floor line at the west heading."[42]

The cost of drilling in the tunnels ranged between $4.50 and $7.00 per foot.

Two shafts were sunk in 1925 on the St. Lawrence River near Massena, New York, and horizontal wells drilled therefrom in connection with studies of the proposed Barnhart Island power house. One shaft was sunk 62 feet to rock and deepened 27 feet into hard limestone to a total of 89 feet. It was about 6 by 8 feet in cross section, and a chamber was enlarged at the foot. "Three horizontal diamond drill holes 2 inches in diameter were drilled. The first hole was 660 feet in length and was discontinued because of its downward dip. The second hole was started with an upward inclination of 1½ per cent, and was abandoned at 350 feet because of the downward dip. The third hole, started with an upward inclination of 3 per cent, was 760 feet long. Its end was then 4 feet below the starting point . . .

[42] Cleaves, Arthur B., Letter to author.

"The Long Sault shaft encountered rock at 22 feet below the surface. This proved to be a bed of limestone only ten inches thick underlain by a four foot layer of shale and separated therefrom by an open seam. The seam was grouted and the shaft carried down 61 feet below the surface . . . The shaft was timbered to a cross section of 6 by 8 feet in the clear. A single horizontal boring was made from this shaft which was 691 feet long. It dipped downward 15.7 feet in its length."[43]

Surveying devices and wedges or "whipstocks" have been developed for deep vertical oil wells and are made and sold or rented by several concerns.[44] A spectacular example of controlled directional drilling was the recent successful extinguishing of a burning oil well that had formed a crater, by drilling an offset well and directing it to within a few feet of the foot of the burning well. Water pumped down the offset well flooded the oil sand in its vicinity and stopped the fire.[45]

Ranney[39a] states that devices have been developed to make a continuous and accurate survey of a horizontal hole, but they were not used on his horizontal well. He also claims to be able to control the direction of the hole while drilling. Apparently these devices are still in the experimental stage, and it is doubtful whether accurate control of a horizontal hole more than 1000 feet long is possible at the present time, though it may be in the future.

In the past the cost of drilling horizontal diamond drill holes has ranged between $4.50 and $10.00 per foot. These costs were based on a comparatively small footage drilled per installation of machinery. It appears likely that as the method improves the cost will be in the neighborhood of $2.00 per foot. In making estimates it would be safer to assume $3.00 per foot to provide for overhead, including the ventilation of the chamber while drilling, and adverse drilling conditions such as pebble beds which may be found in certain sands. Although the drilling of a large amount of footage from a single set-up would decrease the costs, the drilling to depths greater than 1000 feet probably would increase them. This increased cost would tend to be offset by the fact that a larger area could be developed from each shaft.

It is consequently impossible to predict the area that can be developed from each shaft. Probably the most important factor will be the local sand conditions.

If the shaft is sunk at the center of a hexagonal tract with sides 1000 feet long containing 60 acres, and if 12 wells are drilled radially at intervals of 30°, the maximum depth will be 1000 feet and the wells will be about 500 feet apart at the boundaries. The total footage drilled would be about 11,100 feet. If it is assumed that it will be possible to drill 2000 feet, 24 holes may be drilled from a single chamber. The spacing of the wells will be 522 feet, 2000 feet from the center. If the shaft is at the center of a hexagonal tract with an area of 238 acres there will be

	Feet
6 wells 2,000 feet long	12,000
6 wells 1,732 feet long	10,392
12 wells 1,793 feet long	21,516
Total	43,908

[43] Richards, Lieut. Col. George A., Letter to author.
[44] Eastman Oil Well Survey Corp., 2869 Long Beach Blvd., Long Beach, Cal.; Sperry-Sun Well Surveying Co., 108 Walnut St., Philadelphia, Pa.; Lane-Wells Co., 5610 South Soto St., Los Angeles. Calif.
[45] Williams, Neil, Cratering well is killed by drilling offset: Oil and Gas Journal, Oct. 8, 1936.

If the shaft is at the center of a square tract with an area of 185.8 acres there will be

	Feet
4 wells 2,000 feet long	8,000
4 wells 1,414 feet long	5,656
8 wells 1,464 feet long	11,712
8 wells 1,633 feet long	13,064
Total	38,432

The foregoing calculations were based on the assumption that the horizontal wells should be 500 ft. apart at the outside. It may be advisable to use a closer spacing. It may also be possible to drill branching holes in order to decrease the spacing in the outer parts of the lease.

In estimating costs it will be assumed that 40,000 feet of hole, covering 200 acres, may be drilled from each shaft.

SHOOTING HORIZONTAL HOLES

Nearly all oil sands have a very low vertical permeability; that is, fluids can flow parallel to the bedding but not up and down. This is partly because the sand and mica grains during their deposition settled with their longer axes horizontal, but chiefly due to the thin beds, stringers, or "breaks" of shale which are commonly found in all sandstones and are quite impervious. Consequently, a horizontal well, if not shot, would drain only the part of the sand immediately opposite the hole, and would have little effect on the parts above or below it. This fact has been generally neglected in most of the previous articles on oil mining. It is doubtful whether short vertical holes drilled up or down from tunnels would effect good recovery unless they completely penetrated the sand. The "unexcavated draininge channels" of Ranney[28 29] probably would not be formed in the type of sand body common in the Pennsylvania fields. It seems imperative, therefore, that a charge of explosive be set off in the hole in order to crack the sand vertically and thus tap upper and lower beds.

Little is known of the actual cracking effect of a shot in an oil well owing to the practical impossibility of observing what happens. Rock chips blown from a well during a later shot have shown that the best developed open cracks, subsequently filled with calcite or gypsum, are in planes radial about the axis of the well. It has been suggested that these cracks were due to periodic vibrations set up by the impact,[46] but it seems likely that they are also due to tension produced by the immense pressure developed in the hole, causing the rock particles to move outward, thus setting up tensional stresses in a circumferential direction. For either vertical or horizontal wells it would seem that the formation of these radial cracks is the effect most to be desired.

The hole drilled by Mr. Ranney was shot for 546 feet, and subsequently he estimated that 250 barrels of sand were removed, which would indicate that the diameter of the hole was increased to 21 inches. However, the effective increase in diameter was probably much greater. By comparing the quantities of water taken in input wells in the Bradford field before and after shooting, Dr. S. T. Yuster[47] has calculated that in

[46] Bossler, R. B., Theories and practices in modern oil well shooting: Oil and Gas Journal, July 20, 1939.

[47] Saxe, A. J., and Yuster, S. T. Mathematical analysis of oil field results: Producers' Monthly, Jan., 1938.

some cases the "effective radius" of the well was increased from 3 inches to 20 feet. That is, the hole was not enlarged to a diameter of 40 feet, but the radial cracks exposed so much surface that as much water was taken as if it had that diameter. The increase in the amount of air taken in a shot hole is not usually as great as the increase in the amount of water.

It is difficult to imagine the effect of a shot in a horizontal well. While Mr. Ranney's well was being shot, an engineer placed several ten-penny nails on a plate on the hilltop over the well and separated from the well by about 250 feet of cover. At the detonation the nails jumped 1½ inches into the air; however, this does not indicate, as has been stated,[29] that the surface moved that amount. It seems likely that radial cracks were developed extending out into the sand for many feet. Those in a horizontal plane, because of the small thickness of overburden, probably opened wider than those in a vertical plane, but the weight of the overburden would tend to close them more. The writer believes that the situation is quite different from shooting a vertical well. In that case the well penetrates all the units of the sand, and the purpose of shooting is to increase the exposure of surface of each unit and thus to decrease the crowding of the flow-lines which converge towards the bore hole. This purpose is admirably effected by radial cracks. In a horizontal well, on the other hand, the unit at the same level as the bore-hole is entirely opened, and the flow-lines are parallel into the hole. The purpose of the shot is to form channels to the units above and below the hole. If we postulate a very low permeability for the sand, and assume that the principal effect desired is to open up beds of sand not opposite the bore hole, the writer believes that the horizontal component of the shot cracks may be disregarded. The effect of the shot may then be considered to be the formation of a vertical crack or channel from top to bottom of the sand.

In order to insure, as far as possible, the formation of these cracks, the hole should be shot as heavily as possible. Probably four pounds of high-velocity gelatine should be used per foot. The cost is estimated to be about $1 per foot; 50 cents per foot for the dynamite, 15 for the fuse, 10 for the cartridge, and 25 for the labor of charging, shooting, and cleaning out after the shot.

APPLICATION OF SECONDARY RECOVERY METHODS

The enormous increase in surface exposed will greatly facilitate the motion of the oil toward the wells. However, with no expulsive gas left in the sand, gravity drainage alone will not be efficient in removing most of the oil. The low vertical permeability means that the oil must flow parallel to the bedding, and in a gently dipping sand gravity will have little effect in making it do this. Some expulsive method must therefore be used.

The writer believes that water flooding will not prove very effective. Except at Bradford, water flooding has seldom been successful in Pennsylvania. The reasons for its failure are that (1) the sandstones have too high and too variable permeability, (2) the initial oil saturation of the sand is low. It has been indicated that flooded-out properties in Bradford may have a residual oil saturation of 20 per cent or more,[48] although in the middle fields properties with this saturation have responded to air repressuring. Repressuring with natural gas or the use

[48] Fettke, Chas. R., The Bradford Oil Field: Penna. Topo. & Geol. Survey, 4th series, M 21, p. 413.

of solvents to decrease the viscosity of the oil are probably too expensive. The most attractive expulsive agent is air.

Mr. Ranney suggests making alternate holes pressure-intake wells. He proposes to line all but the last 200 feet of the pressure wells with thin cement, and to shoot the last 200 feet. Instead of lining the hole with cement, it probably would be simpler and easier to set a packer on the end of a string of tubing. After the air has passed through the last 200 feet for a time, until no more oil can be swept out, this part of the hole is plugged with cement, and another 200-foot interval shot.

Experience indicates, however, that under this arrangement the air will not be entirely effective in sweeping out the oil because the greater part of it will travel through the most permeable bed and will bypass the oil in the other beds. In vertical pressure wells this tendency is counteracted by separating the more and less permeable streaks by packers and injecting the air at different pressures in different parts of the sand. On the other hand, if the well is not shot the pressure will be effective only on the bed immediately opposite the hole.

A method of controlling bypassing which may be practical was proposed by the writer for conventional methods of repressuring. The producing wells are closed, and air or gas is injected into the pressure wells until a considerable pressure is built up and has had time to equalize itself throughout all parts of the sand. The producing wells are then opened and the air allowed to escape, bringing with it the oil from the tight as well as from the loose parts of the sand. The cycle may take several days, and can be repeated indefinitely. Difficulties are the presence of poorly cased holes and the possible loss of oil at the lease boundaries.

It might be advisable to drill vertical pressure wells in which packers could be set, between the horizontal producing wells. The air could then be injected at different pressures in different beds of sand. However, unless the vertical pressure wells were spaced closely along a radial line, the air would tend to flow directly towards the horizontal wells, and considerable areas of the sand would be unaffected. In the central part of the tract especially, the wells would have to be spaced very close together.

Drilling horizontal wells probably will increase the rate of recovery over conventional methods because of the larger surface of sand exposed. Mr. Ranney's experimental well also seems to indicate this, but does not provide accurate data. It seems to the writer futile to attempt to predict what the increase will be. It would certainly be unwise to assume that the increase in rate will be directly proportional to the increase in surface exposed. There is no reason to assume that the decline curves of horizontal wells will have the same shape as ordinary decline curves. It seems probable that during the early life of a horizontal well, the decline curve would drop less rapidly than that of a vertical well, and that later it would drop more rapidly, so that eventually the curves would cross. Data from several horizontal wells on steady production must be assembled before any well-founded predictions can be made.

The fact that in the Pennsylvania fields wide variations of permeability are present in a horizontal direction has long been known. Dry holes have often been drilled between two good producers. An increase in the surface of sand exposed to a well therefore has the additional effect, not considered above, of tapping some volumes of sand which are

sealed off, or partially sealed off, by these horizontal variations in permeability. This will result in an increase in the ultimate recovery of oil.

In the hard, dense, and usually fine-grained sands of the Pennsylvania fields, gravity is considered to be almost ineffective as a means of propelling the oil from the sands. The original gas pressure has been dissipated, and pressures of water or gas must be applied artificially. In this case the drop in pressure per unit distance is the important factor in moving the oil. Under the usual patterns of vertical wells the greater part of the pressure drop takes place in a comparatively small area in the immediate vicinity of the injection and producing wells, owing to the convergence and crowding of the flow lines. An increase in surface of sand exposed would lessen the crowding and make greater pressure drops in the sand out between the wells. This might result in more efficient and possibly increased recovery. The writer, however, does not subscribe to the statement that the percentage of oil recovered, of that originally present, may be increased from 20 to 40 per cent to 60 to 80 per cent.

Obviously even under ideal conditions in which every part of the sand is exposed to the flushing of sand or water, a considerable quantity of oil must remain held on the sand grains by surface tension and absorption. In water flooding the use of detergents to assist in the removal of this oil has been suggested but has not proved practical in Bradford.[49]

The use of solvents to remove some of this oil film has been suggested. It might be possible to introduce petroleum condensate (natural gasolene) in liquid form in intake wells, and to recover it from producing wells, partly as gas and partly as liquid in which much of the crude oil would be dissolved. When it became no longer worth while to circulate the petroleum condensate, almost all of it could be recovered by the application of vacuum.

COMPRESSOR PLANT

In the Titusville-Oil City area it is usual to arrange the pattern so that there is one pressure well to four or six producing wells with a spacing of 200 to 250 feet, or about one pressure well to five acres. Air is injected at the rate of 1000 cubic feet per day per vertical foot of sand. Two to six packers are set and the air is injected into the different parts of the sand at different pressures, which are adjusted so that that amount of air is taken by each part of the sand. Pressures range between 250 and 400 lbs. per square inch. As the sand is mostly 20 to 40 feet thick, between 7000 and 12,000 cubic feet of air per acre per day are injected. As the wells are about 6 inches in diameter, about 300 cubic feet per day are injected per square foot of surface exposed.

Mr. Ranney suggests that in a pattern of 24 radial wells from the foot of a shaft, 12 wells be used for pressure wells, and that 200 feet of each well be shot simultaneously. In a 30-foot sand this would expose 144,000 square feet of surface. It would then be possible and probably necessary to inject far larger quantities of air than is customary under conventional methods, but at much lower pressures. Reciprocating compressors would not be suitable, but turbo-blowers are capable of delivering from 4000 to 12,000 cubic feet per minute at discharge pressures up to 100 lbs. per square inch.

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[49] Fettke, C. R., The Bradford oil field: Pa. Geol. Survey Bull. M. 21, p. 433, 1938.

It will be clear from the foregoing that many variables and uncertainties enter into any estimates of the cost of this method of oil recovery, but such estimates must be made to determine its economic feasibility. In the following estimates no attempt has been made to arrive at either maximum or minimum figures. They have been compared with independent estimates made by experienced mining and petroleum engineers. If anything, they are probably too low, as allowance for unforeseen difficulties and problems has not been made, and the new method is given the benefit of the doubt.

It will be assumed that the method will be tried in an area underlain by one sand, not over 30 feet thick, at a depth of 500 feet, and that the horizontal holes can be drilled to a depth of 2000 feet, thus developing 200 acres from one shaft.

Development costs. Before operations begin, vertical core wells must be drilled to determine the oil content of the sand. They will also determine the probable gas pressure that may be encountered, and the thickness, character, and position of the oil sand. The least number would be one well in the center of the tract at the site of the shaft, and four others, each half-way to the lease boundary; a total of five wells, or one well to 40 acres.

Cores taken with cable tools are generally believed to be less satisfactory than diamond cores. Less core is obtained, and it is broken in small "biscuits." There is more danger of contamination and washing out of the fluids in the core by drilling water, so that the determinations of oil content are less accurate. The hole at the site of the shaft should be diamond cored throughout its whole depth, and the other wells should be cored in the sand. $1000 is allowed for the central well, and $500 each for the others. A sum of $2000 additional should be provided for surveying, geological examination, and accurate analysis of the cores.

As stated, $37,500 may be allowed for the shaft sinking and $5,000 for the enlargement of the working chamber. These items may be too low, especially if, as will probably be the case, a single shaft is sunk for experimental purposes. If more than one shaft is sunk, the rental or amortization of the necessary equipment would be spread over a larger footage. The four holes around the periphery of the shaft will cost about $1500 and $500 additional may be allowed for the cement and labor of grouting. This item may be too low since such holes often take large quantities of cement.

Hoisting and ventilating equipment will have to be permanently installed at each shaft. Since nothing except men and occasionally some machinery will need to be hoisted after the drilling is finished, very heavy duty equipment will not be necessary. In order to eliminate the necessity for a hoist engineer, probably the cage can be controlled electrically like modern elevators.

Probably two fans for each shaft will be required, the second to operate on an auxiliary motor in case of accident to the main fan. $10,000 will be allowed for the permanent hoisting and ventilating equipment.

$3 per foot will be allowed for drilling the horizontal holes. If 40,000 feet are drilled the sum will be $120,000.

Each producing hole will require 50 to 100 feet of casing cemented in,

pipe fittings, and gauges. The pressure wells may require tubing and packers as well. $200 per well is allowed, or a total of $4800.

Shooting 37,500 feet of hole at $1 per foot would cost $37,500.

The oil and water produced will be lifted to the surface either together or separately by pumps, probably operated by a gas-proof electric motor. $5000 is allowed for the purchase and installation of this equipment.

As it is impossible to estimate the quantity of air that will be required for repressuring, it is hard to arrive at a figure for the cost of installing a pressure plant. If the possibility of bypassing is to be disregarded and the air cycled continuously, turbo-blowers will be required, probably able to deliver 5000 cubic feet of air per minute at 75 or 100 pounds pressure. If a high pressure pulsating system will be used, reciprocating compressors capable of delivering 1500 cubic feet per minute (about 2,000,000 cubic feet per day) at pressures up to 400 pounds per square inch will be used. $30,000 may be allowed for this item.

As on an initial venture the best technique of mining and petroleum engineering will be necessary, and many unforeseen difficulties undoubtedly will occur, it will be wise to add 20 per cent of the total development costs to provide for supervision and engineering, and contingencies. This will amount to $60,000.

Operating costs. The enterprise, to be successful, should pay for itself in less than ten years.

Each shaft probably will need a pumper on duty at all hours. If there are several shafts, a superintendent can divide his time between them. Labor costs per shaft per year are estimated as follows:

3 pumpers at $1,800 per year	$5,400
1/3 superintendent's time at $2,400 per year	800
¼ engineer's time at $4,000 per year	1,000
	$7,200

Until the type of plant is known, and whether it will be operated by gas or electricity, it is impossible to estimate the power charges. They will be assumed to be $5000 per year.

A considerable sum should be allowed for repairs and improvements to the surface equipment, well equipment, pumping equipment, and pressure plant during the ten years of operation. This sum is estimated as $25,000.

Although it is possible that some marketable oil may be obtained soon after the first horizontal well has been drilled, large returns can hardly be expected for at least two years after the project is undertaken. Cost accountants differ as to whether interest should be included in operating costs, but interest payments will probably be unavoidable, and certainly should be charged off before the enterprise can be said to be a commercial success. For a rough estimate of their amount it will be assumed that half of the total development cost will be raised the first year, the rest the second year, and that during the third year one-eighth of the cost will be amortized, during the fourth year two-eighths, and so on.

Year	Cost	Interest at 6 per cent	Year	Cost	Interest at 6 per cent
First	$178,400	$10,704	Sixth	223,000	13,380
Second	356,800	21,408	Seventh	178,400	10,704
Third	356,800	21,408	Eighth	133,800	8,028
Fourth	312,200	18,732	Ninth	89,200	5,352
Fifth	267,600	16,056	Tenth	44,600	2,676
			Total interest		$128,448

Taxes. In some counties in Pennsylvania, oil property is assessed at $500 per barrel of production per day. It will be assumed that the oil mining development will produce 600,000 barrels in ten years from 200 acres. Taxes may be estimated as follows:

Barrels per day, 164; assessed valuation, $82,000; taxes at 40 mills, $3280 per annum.

Income and corporation taxes have not been estimated.

Summary of costs. Development of a 200-acre tract by means of a shaft 500 feet deep with 24 horizontal wells drilled radially to its boundaries.

Development costs	
Land at $200 per acre	$40,000
Exploratory bore holes	5,000
Shaft	
4 holes for grout, and grouting	2,000
Sinking and lining shaft at $75 per foot	37,500
Hoisting and ventilating equipment	10,000
Excavating and lining working chamber	5,000
Horizontal wells	
Drilling 40,000 feet at $3 per foot	120,000
Equipping 24 wells at $200 per well	4,800
Shooting 37,500 ft. of hole at $1.00 per foot	37,500
Purchase and installation of pumps	5,000
Compressor plant	30,000
Contingencies, engineering, and supervision	60,000
Total development cost	$356,800
Development cost per acre	1,784
Operating costs (ten years)	
Labor	72,000
Power	50,000
Repairs and improvements	25,000
Interest charges	128,448
Taxes	32,800
Total operating costs	$308,248
Operating cost per acre per year	$154.12
Total development and operating costs	$665,048
Total cost per acre	$3,325

It should be obvious to any mining or petroleum engineer or business man that an initial attempt at oil mining should be made only in an area that is known to contain comparatively large quantities of oil, both from analyses of the cores and from production records. It may well be that as the method is developed it will be found possible to recover oil commercially from areas that are not profitable under present methods of production. Mining oil by the methods here discussed involves so many unknown factors and so many techniques to be worked out by trial and error that the first attempt unavoidably will be slow and expensive. If only small production is obtained, the operators and in-

vestors will be seriously discouraged, and may lose substantial sums of money. There will be a strong temptation for an operator who is unable to show a profit on his leases under present methods of production to attempt to mine them in the hope of greater returns.

Many leases in the Pennsylvania fields show, according to current methods of oil sand analysis, 8000 to 10,000 barrels of oil per acre in a single 25 to 40 foot sand. Under present methods of production by repressuring from 2000 to 3000 barrels of oil per acre may ultimately be recovered. It may be expected that by mining methods 3000 to 5000 barrels of oil per acre may be recovered during the first ten years of operation. According to the preceding cost estimates, if 3000 barrels per acre are recovered the cost per barrel will be $1.11; if 5000 barrels are recovered the cost will be $0.66.

LEGAL AND ECONOMIC CONSIDERATIONS

In the preceding cost estimates account was not taken of several factors which may have a serious effect on the cost and price of oil produced by mining. Due consideration should be given them by anyone contemplating an oil mining enterprise.

Patents

The author has not attempted to make a thorough study of the numerous patents that have been granted to originators of ideas or devices applicable to oil mining. The legal status of some of them is perhaps questionable. Control over others is held by very powerful interests. It might be impossible to secure a license to operate under some of them if their owners insist on contracting to do the work themselves. To the cost of exploration, a sizable sum must be added for investigation into the legality of numerous patents and for negotiation with their owners. To the cost of development, an additional sum must be provided for license fees, royalties, or litigation.

Land

In the older Pennsylvania fields which are most suitable for oil mining, the land is held in small tracts, usually less than 200 acres. It may be very difficult to secure a block large enough to make the considerable investment safe. The owner of a small lot might be able to hold up development completely. The right to drill under roads, cemeteries, and school lots might be questioned.

Insurance

In a method of mining that holds so many known and unknown dangers, the cost of insurance, especially workmen's compensation insurance, would certainly be high and might be prohibitive. Labor costs should be increased by a considerable amount to provide for this.

Laws

Very strict laws enforced by State mine inspectors govern the mining of coal in Pennsylvania. Different codes exist for the anthracite and bituminous fields. It is doubtful whether either of these codes will apply to oil mining. If oil mining should become widespread, a new code would certainly be enacted to enforce safety measures.

Prices

The Pennsylvania Grade Region offers the most attractive locations for initial attempts at oil mining because, among other reasons, the

crude oil produced commands a price substantially higher than that of other crudes. In contemplating an oil mining proposition it should be borne in mind that this price differential is frequently threatened by (a) increasing competition from western crudes, especially from Illinois and Michigan, (b) production in Pennsylvania in excess of the quantity required to satisfy the rather limited demand for Pennsylvania oil. If a large increase in the production of Pennsylvania oil were effected by oil mining or some other method, the costs of production would have to be comparable to those of western crudes.

CONCLUSION

It is the opinion of the author that the recovery of oil by underground methods of mining is technically possible, and that under favorable conditions it will be profitable. The method of drilling horizontal holes from the foot of a shaft seems to offer the cheapest way of opening a large surface of oil sand to drainage, and is, therefore, the most promising of the methods proposed. However, it presents many technical difficulties, especially in the methods of producing the oil after the wells are drilled, which will have to be worked out by experiment.

It cannot be overemphasized that any oil mining project should be undertaken only by a group with large resources, able to acquire a large block of rich land, to use the best technique of mining and petroleum engineering, and to carry the project to a successful conclusion despite unforeseen difficulties. A group without large resources is almost certain to fail, and one or two failures might retard the progress of the oil industry in the State by many years.